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STATUS OF DPIS DEVELOPMENT IN BNL*

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Abstract

Direct injection scheme was proposed in 2000 at RIKEN in Japan. The first beam test was done at Tokyo Institute of Technology using a CO₂ laser and an 80 MHz 4 vane RFQ in 2001, and further development continued in RIKEN. In 2006, all the experimental equipments were moved to BNL and a new development program was started. We report on our recent activities at BNL including the use of a frozen gas target for the laser source, low charge state ion beam production and a newly developed laser irradiation system.

INTRODUCTION

A laser ion source (LIS) is a leading candidate of heavy ion sources for providing intense highly charged beams for high-energy accelerators. The laser power can be deposited within a tiny area of the target material's surface and the evaporation process starts. Successively the evaporated gas absorbs the laser power and becomes plasma. Since the large laser power goes into a very limited volume, huge amount of the highly-charged ions are produced. An emission from a table top small laser easily produce more than 10^{12} W/cm² on a target surface and the total induced current reaches more than a few hundred A.

We have studied LIS since 2000. We proposed direct plasma injection scheme which enables high current heavy ion beam acceleration. More than 60 mA of carbon [1] and aluminum beam accelerations by an RFQ were demonstrated. We have also examined several laser systems and many targets species [2]. Using the measured plasma data, almost any desired species can be used for the LIS except helium gas.

In 2006, our group moved from RIKEN, Japan to BNL, USA with our experimental equipments and we started a new development program in BNL. In this report, we briefly introduce our current activities related LIS and DPIS.

LASER EMISSION CONTROLE

The laser emission control is important to gain good ion beam stability. We are currently using a tabletop Nd-YAG laser system, Thales-SAGA 230/10. When we started to use this laser, we were suffered by laser leakages. The laser consists of two laser cavities, a master oscillator and a power amplifier, and a Q-switch is installed at the oscillator to make a short pulse. The Q-switch controls a polarization and adjusts laser-firing timing. The laser media is pumped by flash lamps. A typical emission of the

flash lamps is indicated as red curve in Figure 1. The flash lamp emission lasts more than 200 μ s and the Q-switch selects certain timing for releasing the pumped energy to maximize laser emission power.

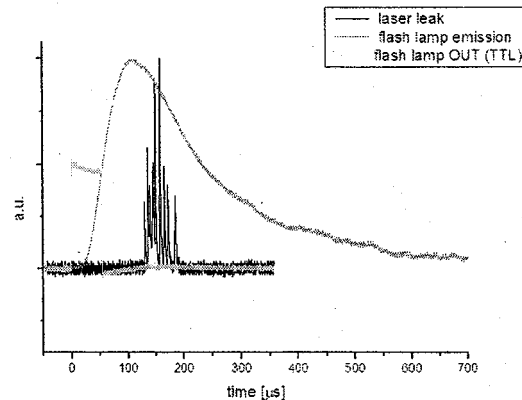


Figure 1: Flash lamp timing and laser leakage.

The laser emission pulse width is typically 6 ~ 9 ns. The flash lamps are always operated at 10 Hz for good stability and the laser emission is only controlled by the Q-switch. While the Q-switch is off position, the laser should not be emitted. However even Q-switch is turned off, very weak laser emission exists. This leakage could not be sensed by a power meter. We observed the leakage by directly seeing the light from the plasma using an IR viewer. The leaked laser energy is very small but is enough to make plasmas and can damage the surface of the target since the leaked energy is concentrated onto a pinpoint by a focusing mirror. To avoid the pre-damage of the target due to the laser leakage, we installed a fast mechanical shutter in the laser path to the ion source. The shutter closes or opens within several ms and this speed is adequate to choose any desired laser pulses because the flash lamps are blinking at 10 Hz. So that the laser shots caused only by the Q-switch are transported to the ion source. Un-desired laser leakages from the un-fired blinking of the flash lamps are blocked. The ion beam stability was dramatically improved. However the laser shutter is not enough to eliminate the negative effects completely. Again in Figure 1, you see the black plot which shows the time structure of the laser leakage when the Q-switch closed. The leakage exists even in the same fired laser pulse. The Q-switch timing is usually selected to maximize the laser emitting power and typically around 180 μ s behind the flash lamp control signal triggered.

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However as it is shown in the figure, before 180 μ s, the leakage starts. The leakage in a single laser pulse is weak and we cannot observe any foot print on the target surface, however this small leakage just before the main pulse of the laser shot has enormous effect to the plasma heating condition. Let us note that this leakage is not considered as "pre-lasing," since this is usually too weak and cannot be detected while you are measuring the main laser pulse power. Therefore the Q-switch timing should be selected before the leakage starts or after the leakage ends. Base on our experience, it is suggested to wait for more than several μ s past after the leakage ends for the Q-switch timing. The behavior of the laser leakage depends on the type of Q-switch. The careful timing settings are required for the good ion beam stability. The investigation of the performance of the Q-switch and its timing are still continued.

FROZEN TARGET

Although LIS had only used solid target materials, we started to induce plasma from rare gaseous. The idea is quite simple. We used a cryo-cooler head, Sumitomo RDK-408D2, to condense gases and the solidified targets were tested in BNL. Ar and Ne were successfully used to provide intense beams. We also tried hydrogen, but the cooling power or a heat shield was not enough and could not get stable beams. Figure 2 shows the detected charge states from the Ar experiment.

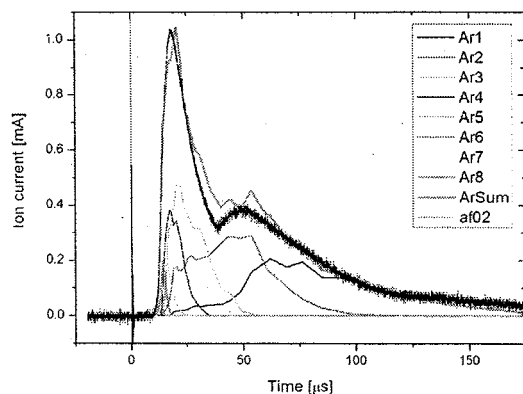


Figure 2: Analyzed Ar plasma. The currents are measured at 2.4 m from the target. The aperture size of the Faraday cup was 10 mm in diameter. The laser was set to 1200 mJ with a second harmonic crystal (532 nm). The applied laser power density on the target was about 5×10^9 W/cm².

The cryo head could be cooled down to 4.5 K that temperature was low enough for almost any gases except helium. At the beginning of the experiment, the gases were fed by a thin plastic pipe, less than 1 mm in diameter, to spray directly to the target surface however this structure was not necessary. The gas could be fed into the vacuum chamber without the nozzle and the pressure was controlled not to exceed 10^{-4} Pa. The residual gas was

mostly the fed molecules and those were caught by the cold surface automatically. The cold surface was coated by several layers of the molecules and those were enough to provide the desired plasmas. Once laser was shot, the surface became clean and the surrounding area was also flashed by the conducted heat. The accumulated layers always started on the fresh cold surface and were in same condition for every laser shot. The reproducibility was quite good. On the other hand, rapid cycle was not applicable and more than a few seconds were needed as an interval. To increase the repetition rate, a differential pumping system will be required. We plan to accelerate the rare gas atoms by an RFQ in the near future.

LOW CHARGE STATE BEAMS

By controlling the laser power density on the target, a charge states distribution can be shifted. We are studying low charge ion beam production from the LIS. Generally lower laser power density is better to produce low charge state beam, however there is a threshold value of the density to make a plasma. We tested many materials and most of the material have almost same thresholds which are about 10^8 W/cm². Only carbon graphite showed higher threshold.

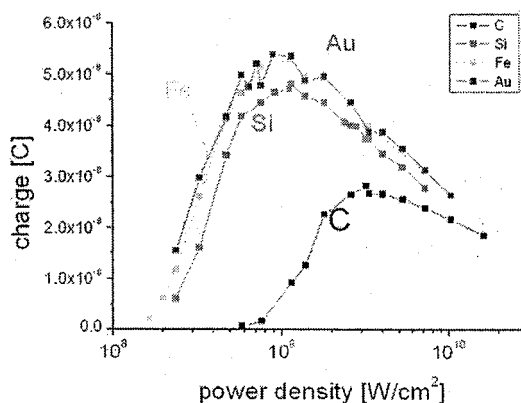


Figure 3: The measured total charges. The laser power density was controlled by changing the position of the focusing lens. The lower density also implies a larger exposure area.

By measuring the velocity distribution of the plasma, the initial plasma temperature was estimated and the obtained temperature was consistent with the first ionization energy of the atoms except the carbon case. We can provide intense low charged ions to the RFQ with the DPIS. This is suitable approach for "heavy ion inertial fusion." Unfortunately we do not have an adequate RFQ to capture the very low charge to mass ratio particles. In the next step we plan to inject the Au¹⁺ beam to our existing 100 MHz RFQ to examine just the transverse motion of the beam.

The low charge state beam from the LIS has another superior advantage. We measured the emittance of the

extracted beam and the obtained values were dominated by an emittance measurement system [4]. The plasma was produced under the high temperature condition but it is adiabatically expanded before the ion extraction process. This means the extracted beam is cold and it might be useful for other applications.

IMPROVED DPIS-LIS

The mechanical structure of the ion source is also developing. To accelerate many kinds of species, the plasma drift length is adjustable in our newly designed DPIS chamber. The plasma drift length is the distance between the target surface and the extraction point where is the entrance of the RFQ linac. The dense plasma is diluted while it travels over the drift length and becomes a required density at the extraction point. To obtain good matching condition of the extracted beam to the acceptance of the RFQ, the length needs to be optimized for a desired current, species and charge states. Our recent study indicated that more than 200 mA of carbon 6+ beam can be matched into the acceptance of the existing RFQ. Also the position of the final focusing element can be adjusted. We had used concave mirrors as final focusing element, however a focused image of the laser light on the target were elliptical. To avoid this effect, a convex lens will be used. The focal distance was shortened from 100 mm to 50 mm and the laser power density can be increased. Unlike ion beam optics, there is a diffraction limit for the laser light as the minimum spot size, however we still expect a reasonable improvement. Figure 4 shows the new ion source vacuum chamber which is being constructed in BNL. We also developed a winding system to roll a plastic tape which protect the final focusing lens from the plasma exposure.

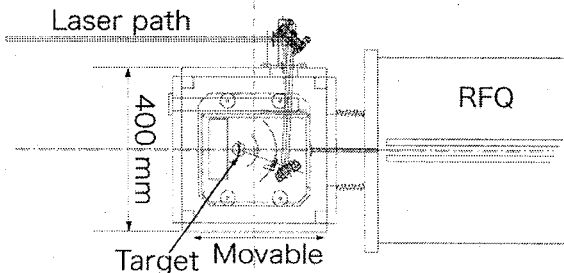


Figure 4: New DPIS set-up.

RFQ

The existing RFQ was designed and fabricated in 2003 [5]. Due to a limitation of a radiation safety regulation in a facility where the beam commissioning was carried out. The output energy was restricted to 100 keV/u, however the acceleration is achieved within the first 1.42 m of the

RFQ. The rest of the RFQ length is 0.5 m and this section has un-modulated vanes. In the un-modulated section, only transverse confinement force exists and consequently longitudinal bunch structure is completely lost.

This RFQ is already connected to a 300 kW RF power amplifier and the high power test was done. At 220 kW RF power input, X-ray emission was measured as 120 $\mu\text{rem/h}$ at the tank surface near the RF coupler. Now we are waiting for an approval for the beam operation in BNL. Using newly optimized condition, carbon beam will be produced and accelerated in next month.

The RFQ has 4 rod structure and the resonator including vanes can be replaceable. The next version of the resonator was already fabricated. The basic parameters of the existing resonator and the new one are listed in Table 1.

Table 1: Basic parameters of the DPIS RFQ.

	Type I	Type II
Design beam	C^{4+} 100 mA	Ag^{15+} 15 mA
Frequency	100 MHz	100 MHz
Duty factor	0.1 %	0.1 %
Inter vane voltage	120 kV	73 kV
Injection energy	20 keV/u	8.3 keV/u
Output energy	100 keV/u	270 keV/u
Cell number	118	143

SUMMARY AND PLAN

As mentioned above, the intensive plasma extraction studies were done in BNL. The feasibility of the frozen gas target was also proved. Many small but important improvements were adopted in the new ion source chamber. A higher current and higher quality beam is expected using the DPIS.

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